# MAJOR ADVANCES FORESEEN IN HUMIDITY PROFILING FROM THE WATER VAPOUR LIDAR EXPERIMENT IN SPACE (WALES)

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The first active humidity profiling system in space is being developed by the European Space Agency (ESA) in the horizon of 2010. Data quality in terms of vertical resolution, accuracy, low bias, and vertical extent is expected to be unsurpassed.

There are pressing needs for high-quality water vapor observations to fulfill societal and scientific requirements in environmental understanding and operational weather prediction. At one level, these needs arise from requirements for more reliable information about the earth's climate system (Houghton et al. 1996, 2001) and closely related needs for improved weather forecasts (Weckwerth et al. 1999; Koch et al. 1997; Bell and Hammon 1989; Crook 1996). Current major research programs of the World Climate Research Programme (WCRP)—namely Stratospheric Processes and their Role in Climate (SPARC) and the Global Energy and Water Cycle Experiment (GEWEX) Water Vapour Project (GVaP)—identify as a matter of urgency the need for an absolute standard for water vapor observations, with global coverage, high accuracy, and good spatial resolution (GEWEX 1998a,b; WCRP 2000).

Data obtained from ground-based and airborne differential absorption lidars (DIALs) have proven the ability of the DIAL technique to meet these needs in terms of good vertical resolution, high precision, and low bias (Browell and Ismail 1995; Wulfmeyer and Bösenberg 1998; Ehret et al. 1999; Bruneau et al. 2001a,b). We argue that a spaceborne DIAL in the 2008–12 time frame would be a major advance, by achieving global coverage together with the high quality offered from the active remote sensing technique (Browell et al. 1998). These anticipated benefits motivated the European Space Agency (ESA) to develop the Water Vapour Lidar Experiment in Space (WALES) mission (ESA 2001). In October 2001, the scientific merit of WALES was successfully presented

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by the authors of this paper in a competition involving five candidate Earth Explorer Missions (EEMs). As a result, WALES is one of three missions selected for "phase A." A major component of this phase is to address all elements of the mission architecture in sufficient detail to facilitate a conclusion on its feasibility. A final decision to implement the mission should be made in early 2004.

It is important to appreciate the goals of ESA EEMs (ESA 1998), which are (a) to provide data essential to earth system modeling and research and (b) to demonstrate the feasibility of new space-based observation techniques of potential application in operational observing systems. Consequently, such missions are developed with the active involvement of industry to solve outstanding technical challenges. Success here provides the foundation for future missions to address applications in atmospheric sciences that require long-term datasets and/or operational missions. Thus, the WALES mission will demonstrate

- the technical maturity of spaceborne DIAL, including continuous operation for at least two years,
- its expected performance with respect to the accuracy and the resolution of the water vapor retrievals,
- the expected impact on NWP and climate research by application of the available dataset, and
- an unsurpassed accuracy so that WALES can be used as a calibrator for other sensors.

Among the technical challenges being addressed in phase A, the main one concerns the development of a suitable laser transmitter system. The proposed spaceborne DIAL will have its roots in the various ground-based and airborne lidar systems that are operated at different research institutes (Bruneau et al. 1991; Wulfmeyer and Bösenberg 1998; Browell et al. 1998; Ehret et al. 1999). While the achievement of laser spectral requirements in terms of line width, frequency stability, and spectral purity in the spectral region considered for WALES (925–940 nm) has been demonstrated at lower laser power (Ehret et al. 1998), the upgrade of the laser power to the required 10 W is challenging, but the accomplishment of this task will strongly benefit from the atmospheric laser Doppler instrument (ALADIN) lidar for the Atmospheric Dynamics Mission (ADM/Aeolous) and redevelopment of the atmospheric lidar (ATLID) for the Earth Clouds, Aerosol and Radiation Explorer (EarthCARE) mission, where part of these critical components are already in the stage of being breadboarded.

The objective of this paper is not to report on technical solutions, but rather to show that the WALES mission will be of substantial benefit to both NWP and climate research. It is well recognized that water vapor effects dominate the earth's climate. Water vapor's radiative properties make it the most important greenhouse gas, and it plays a direct role in other major atmospheric processes including the formation of clouds and precipitation, surface and chemical processes, and dynamics (see Fig. 1). Microphysical processes involving atmospheric aerosol and leading to the formation and development of cloud and precipitation are strongly dependent on the water vapor distribution. Atmospheric water vapor has both direct and indirect effects on the radiation budget of the atmosphere (Elliot and Gaffen 1995). Climate sensitivity to increasing $CO_2$ is primarily dependent on water vapor feedback mechanisms taking place in the middle and upper troposphere (Sinha and Harries 1995). Furthermore, atmospheric dynamics at all space scales is strongly dependent on the variability of the atmospheric humidity field. The water vapor distribution is determined by the hydrological cycle. Water vapor is much less well mixed than other greenhouse gases because of its strong links with temperature and because of the interactions between clouds, convection, and atmospheric transport, especially in the upper troposphere and lower stratosphere. Because of these characteristics, water vapor has high variability in space and time. Together with its large dynamic range, this variability represents a major challenge for its observation.

The main terrestrial sources of humidity data are currently land and ship synoptic reports, buoy data, and radiosonde soundings. Space-based humidity estimates are typically derived from passive infrared and microwave sensors, the global positioning system

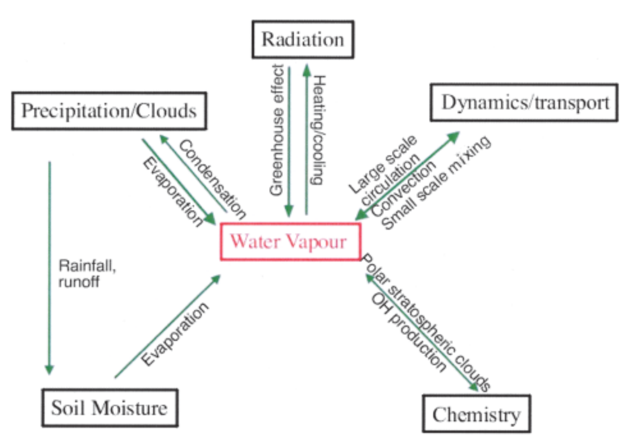


**Fig. 1. The role of water vapor in the earth's atmosphere.**

(e.g., Rocken et al. 1993) for total column water vapor estimates, and from less routine research missions [e.g., the Halogen Occultation Experiment (HALOE) and Microwave Limb Sounder (MLS) instruments on the *Upper Atmosphere Research Satellite* (Russell et al. 1993; Barath et al. 1993)]. Although the benefit from these sources of data has been proven, it is nevertheless acknowledged that each of these suffers from an incomplete and insufficiently accurate description of atmospheric humidity in its spatial and temporal dimensions. For a comprehensive assessment, see the SPARC report (WCRP 2000). The combination of all these sources still leaves us with enormous gaps in our knowledge of humidity, notably in the lowermost stratosphere (tropopause region) and in the presence of clouds (see ESA 2001). In addition, everywhere, and especially over oceans, humidity information suffers from poor vertical resolution.

The remainder of the paper is as follows: the section titled "WALES observation characteristics" first describes the WALES observation principle and then lists the desired specifications in relation to NWP and climate needs for an absolute standard for water vapor data. "WALES versus passive infrared measurements" quantifies the benefits of WALES' data over advanced IR soundings (the best alternative in the 2010 time frame) in NWP applications, stemming mainly from good vertical resolution, low random errors, and improved vertical extent. "Specific impacts" highlights a number of other important contributions to research in NWP and climate. Conclusions are given in the last section.

## WALES OBSERVATION CHARACTERISTICS.

*Observation principle.* WALES is intended to profile the atmosphere in a nadir-viewing configuration. A detailed introduction in DIAL methodology is found in Ismail and Browell (1989) as well as in Bösenberg (1998). The DIAL technique compares the attenuation of two laser pulses emitted at a pair of closely spaced wavelengths (see Fig. 2). The on-line wavelength ($\lambda_{on}$) falls on the center of a water vapor absorption line, and the off-line wavelength ($\lambda_{off}$) falls on the line wing, where absorption is significantly reduced. The water vapor number density as a function of range (height) is directly derived from the on- and off-line measurements from the following expression:

$$n_{H_2O}(R) = \frac{1}{2(\sigma_{on} - \sigma_{off})\Delta R} \ln \frac{P_{off}(R_2)P_{on}(R_1)}{P_{on}(R_2)P_{off}(R_1)}, \quad (1)$$

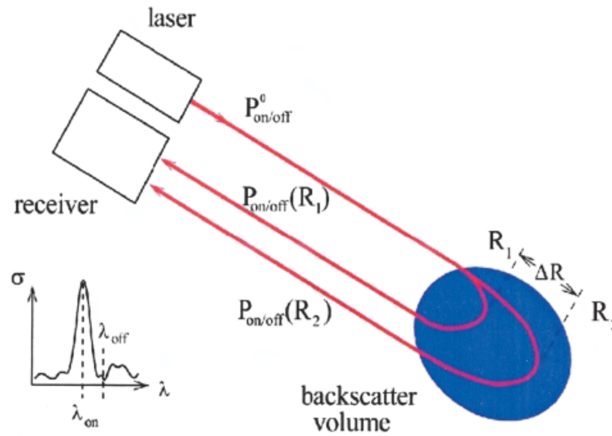


**FIG. 2. Conceptual drawing of the DIAL principle.**

where $P_{on}$ and $P_{off}$ are the backscatter powers at $\lambda_{on}$ and $\lambda_{off}$, respectively; $R_1$ and $R_2$ are the lower and upper levels (heights) of the scattering volume, respectively; and $R=(R_1 + R_2)/2$ and $\sigma_{on/off}$ are the water vapor absorption cross sections. The expression assumes that backscatter and extinction coefficients from particles and molecules at the on- and off-line wavelengths are identical, implying that the difference between the on and off signals is only due to water vapor absorption. The large dynamic range of water vapor can be addressed using several wavelengths pairs. In the context of WALES assessment studies, a system concept based on the use of three pairs of wavelengths has been considered. The different on-line wavelengths are emitted in a cascade and are characterized by different attenuation cross sections. The DIAL technique is self-calibrating: the measurements depend only on knowledge of the water vapor differential absorption cross section. By laboratory measurements, the line strength of the cross section can be determined to an accuracy of about 2% in the near-infrared spectral region (Grossmann and Browell 1989). Measurements in other regions of interest can be performed with the same accuracy. Chosen lines are characterized by a minimum temperature dependence on absorption. If laser spectral requirements in terms of line width, frequency stability, and spectral purity are satisfied and if it is assumed that the temperature profile is known within 5 K, the resulting overall systematic error from Eq. (1) is approximately 3%. Laser beam collimation is specified to guarantee eye safety, with a radiant energy density at ground level within the limits of American National Standards Institute (ANSI) standards (ANSI 1986).

In several publications the high accuracy of DIAL measurements has been confirmed on the one hand by theoretical error analyses (Bösenberg 1998). The methodology of DIAL measurements is straightforward and fully understood so that simulations can be performed. On the other hand, a large amount of experiment results demonstrated that DIAL systems are capable of measuring water vapor profiles with an error of less than 5% in the entire troposphere from validation using radiosondes and dropsondes (Browell et al. 1996; Wulfmeyer and Bösenberg 1998; Poberaj et al. 2002). Recently, some discrepancies between different DIAL systems have been observed (Ferrare et al. 2002). The reasons for these deviations are under investigation. Results from the International $H_2O$ Project (IHOP) campaign, which are currently being analyzed with ESA support, will shed more light on this issue. However, these observations do not disprove the statement that DIAL can meet the 5% error level if all system components are working properly. This is confirmed by an excellent agreement between the Lidar Atmospheric Sensing Experiment (LASE), Raman lidar, and microwave radiometer measurements (Ferrare et al. 2002). In the following, we assume that all system requirements are fulfilled so that accurate measurements with this error limit can be performed.

*Observation requirements.* The observation requirements specific to the WALES mission are given in Table 1. NWP model errors drive the random error requirements (see, e.g., WMO 1998, 2000a,b). Following the World Meteorological Organization (WMO) Table 1 lists threshold requirements, that is, the minimum requirements for the mission to be worthwhile, and target requirements, that is, those currently regarded as yielding maximum benefits to NWP and climate research. We expect the target requirements will be met in the majority of cases (profiles). Climate uses of observational data include analysis of trends and processes contributing to variability on all spatial and temporal scales and to validation of climate models (e.g., Karl 1996). A low and time-independent bias is essential for an absolute standard and relates to climate needs: changing humidity by just a few percent affects the spectrum of outgoing longwave radiation by an amount of similar magnitude to that caused by doubling carbon dioxide in the atmosphere (Harries 1997). Stephens et al. (2002) emphasize the need for good vertical resolution in cloud observations. Similar arguments drive the WALES requirements for vertical resolution of humidity, not least because cloud formation depends on the humidity available for condensation. The vertical resolution of WALES is also relevant for validation of climate models, which show sensitivity at such scales (Pope et al. 2001). We regard the high vertical resolution of WALES as a major advance because it complements the good horizontal coverage of existing humidity observation techniques.

Details of the technical specifications of a DIAL instrument to meet these requirements are given elsewhere (ESA 2001). As mentioned above, one option for covering the large dynamic range of water vapor with the required accuracy is to use three pairs of wavelengths: the strongest absorption line pair will measure upper-troposphere and lower-stratosphere humidity (tropopause region), and the weakest pair will probe the lower troposphere.

**Table 1. WALES mission threshold and target observational requirements. Lower troposphere (LT) is ~0–5 km. Higher troposphere (HT) consists of the midtroposphere (MT; ~5 km–10 km, or 300–500 hPa) and the upper troposphere/lowermost stratosphere (UTLS; ~10–17 km, 100–300 hPa). For random error, 1 $\sigma$ denotes 1 std dev [extracted from ESA (2001, p. 38)].**

| | | Threshold | | | Target | | |
|---|---|---|---|---|---|---|---|
| | | LT | HT | | LT | HT | |
| **Requirement** | | | MT | UTLS | | MT | UTLS |
| Veritcal resolution | (km) | 1.0 | 1.0 | 2.0 | 0.5 | 1.0 | 2.0 |
| Horizontal domain | | Global | | | | | |
| Horizontal integration | (km) | 100 | 150 | 200 | 10 | 50 | 100 |
| Dynamic range | (g $kg^{-1}$) | | 0.01–15 | | | 0.001–25 | |
| Random error (1 $\sigma$) | (%) | | 20 | | | 5 | |
| Systematic error | (%) | | | <5 | | | <2 |
| Timeliness | (h) | | | | <3 | | |

As the satellite circles the earth, backscatter signals from consecutive laser shots (with a footprint of 40 m) are averaged over a certain distance referred to as the horizontal integration distance in Table 1. In practice, this quantity will likely be fixed between 50 and 100 km, but the data downlinked to ground is expected to be supplied at around 1-km horizontal resolution. No error correlation exists between adjacent horizontal profiles. Assuming an integration length of 100 km, this means that about 6000 profiles would be collected daily. The DIAL technique used by WALES allows for trade-offs between horizontal as well as vertical resolution and precision in response to different user requirements. DIAL systems can measure cloud tops precisely, and profiling above clouds causes no significant difference in instrument performance. Profiling below thin clouds (optical thickness <0.3) is also possible, as long as inhomogeneities in cloud albedo, backscatter, and extinction can be neglected. Spectral lines near 935 nm were found to be ideal for this application.

It should be noted that while the proposed instrument is nonscanning, scanning lidar systems already exist (Uthe et al. 1998). If WALES successfully demonstrates spaceborne DIAL, scanning could be envisaged for future operational missions. The resulting improvements in representativeness would make such data more useful for calibrating and validating existing humidity observation techniques.

The remainder of the paper identifies the expected benefits of WALES in comparison to existing systems and the resulting impact on NWP and climate. The expected lifetime of two to three years for the mission covers several seasonal cycles and is considered sufficient to demonstrate these benefits.

## WALES VERSUS PASSIVE INFRARED MEASUREMENTS.

***Background.*** The main sources of humidity profiling on a global basis are infrared (IR) and microwave (MW) radiances. Microwave data are less sensitive to clouds than IR. However, surface-sensitive channels are difficult to use over land in particular because of the variable surface emissivity with moisture. Also, the vertical as well as the horizontal resolutions are superior with IR data. Thus, profiling characteristics of IR data are the main standard against which to assess alternative measures. The ultimate limits of IR profiling will be explored soon from missions such as the Atmospheric Infrared Sounder [AIRS; launched in May 2002 on Earth Observation Satellite (EOS) *Aqua* and currently providing data to NWP centers] and the Infrared Atmospheric Sounding Interferometer [IASI; scheduled for 2005 on Meteorological Operational Satellite (*METOP-1*)] using instruments observing the entire infrared spectrum at unprecedented spectral resolution. The goal of this section is to objectively compare the performances of WALES and advanced IR sounders, IASI in particular, through the concept of information content [degrees of freedom for signal (DFS) and analysis vertical resolution (VR), as described in appendix A]. IASI will cover the spectral range 645 to 2760 $cm^{-1}$ with a spectral resolution of 0.25 $cm^{-1}$, which leads to 8461 channels in each IASI spectrum. The information provided by IASI relates to surface temperature, and temperature, humidity, and ozone profiles, as well as $CO_2$, $N_2O$, CO, and $CH_4$ total column amounts (Camy-Peyret and Eyre 1998). This study will focus only on the performance with respect to humidity analysis. The comparison is made for individual profiles. On that basis, the study demonstrates the superiority of the proposed active approach. Clearly, the WALES concept, because it is nonscanning, is not meant to replace humidity estimates from IR sounders. Rather, WALES data will add to the current observation system. In particular, it proposes a new, necessary standard against which advanced passive sounding techniques can be evaluated. For instance, it will allow us to verify to what extent the AIRS and IASI promises are achieved in the real world (e.g., a 10% accuracy on global humidity fields for 1-km layers).

*Comparison between WALES and IASI performances.* The information content of WALES and IASI for specific humidity has been computed on six standard atmospheres: subarctic winter, subarctic summer, midlatitude winter, midlatitude summer, the *U.S. Standard Atmosphere, 1976,* and Tropics. The WALES error computations were obtained with a 100-km horizontal resolution. The information content of IASI is computed using all 8461 channels even though many channels are not sensitive to humidity. The WALES and IASI DFS obtained on the six standard atmospheres are shown in Table 2. We assumed the foreign gases to be well known and adequately simulated by the radiative transfer model. If the spectral bands sensitive to foreign biases are eliminated, that is, if 1636 channels are removed, the DFS is only slightly smaller (by less than 0.2), which denotes a nonsignificant loss of information in the system. Note that all precautions are taken to ensure the most favorable results from the IASI simulations: reduction of the random errors due to the passage from 12 to 100 km (to match the WALES integration length) and no error correlation between adjacent channels. WALES has a larger DFS than

**TABLE 2. DFS associated with WALES and IASI.**

| Selected atmospheres | WALES | IASI |
|---|---|---|
| Subarctic winter | 23.49 | 12.52 |
| Subarctic summer | 23.76 | 16.97 |
| Midlatitude winter | 23.90 | 14.14 |
| Midlatitude summer | 23.21 | 18.90 |
| *U.S. Standard, 1976* | 23.77 | 17.21 |
| Tropics | 23.11 | 19.43 |
| Average | 23.54 | 16.53 |

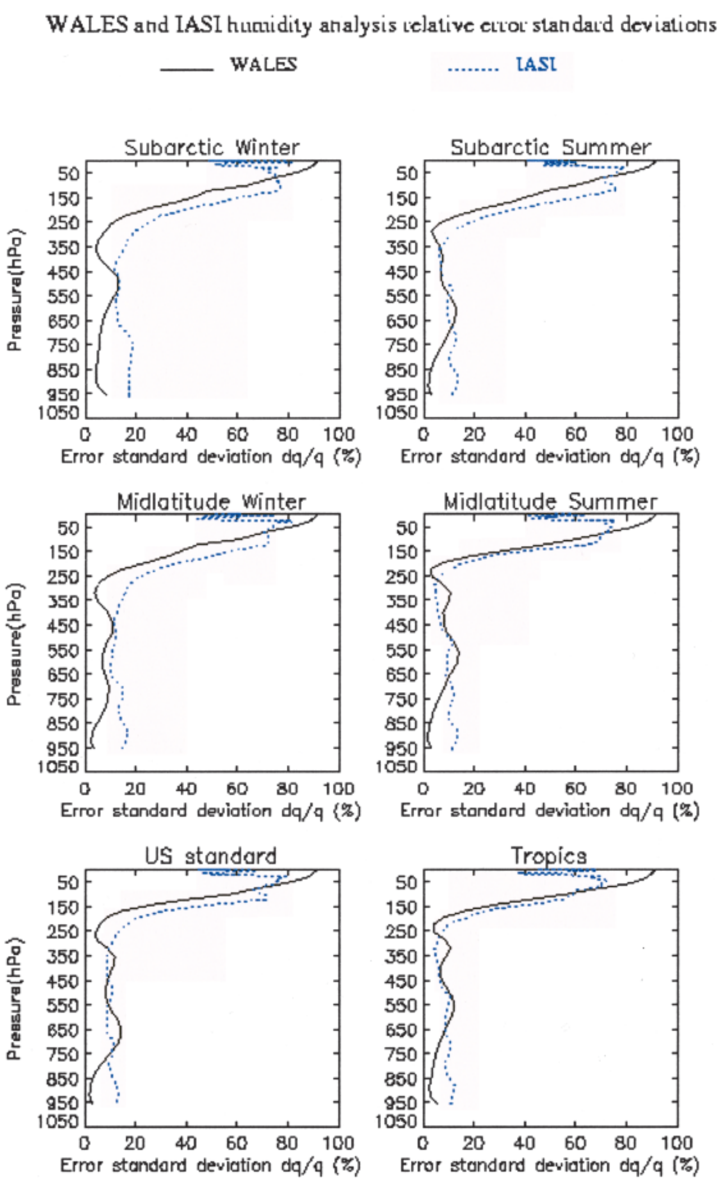


**FIG. 3. WALES (solid black lines) and IASI (dotted blue lines) specific humidity analysis relative error standard deviations for the selected atmospheres.**

IASI for specific humidity, with 7 additional units on average (23.5 for WALES versus 16.5 for IASI), corresponding to about 42% more information in WALES than in IASI. The maximum DFS would be 43, the number of levels used in the computation. However, WALES is designed to get the humidity information up to 100 hPa. Since there are 15 levels above 100 hPa, a DFS of 28 would mean that full resolution is obtained between the surface and 100 hPa. The lower DFS of IASI is the result of both lesser vertical resolution and lesser vertical extent. Table 2 reveals that for WALES, the DFS is largely independent of the type of profiles, while this is not the case for IASI. This occurs because of the higher vertical extent of IASI in warm atmospheres than in cold atmospheres.

Figure 3 shows the error standard deviation of the humidity analysis [i.e., $d\ln(q) = dq/q$)] obtained for WALES and IASI based on Eq. (A1) (see appendix A for equation). WALES globally performs better than IASI, especially in the lower troposphere. The analysis relative-error threshold of 20% is exceeded above 150–200 hPa (12–14 km) for WALES, and above 200–250 hPa (10–12 km) for IASI, which shows a gain of about 2 km on the WALES retrieval vertical extent. Below 250 hPa, where both IASI and WALES meet the 20% accuracy threshold, the mean relative error of WALES retrievals is about 7.2%, while that of IASI is 11.4% These statistics are detailed in Table 3. The relative improvement of WALES over IASI is largest for the subarctic winter profile and lowest for the tropical profile. Note that it is assumed that IASI radiances are free from systematic biases.

Figure 4 shows the humidity analysis VR obtained from WALES and IASI simulations on the standard atmospheres. The "layering" curve is simply the actual thickness of each layer. The WALES analysis vertical resolution is very close to the layering (full) resolution up to about 150–200 hPa, whereas IASI values of VR are always much larger, and again the vertical extent does not exceed 200–250 hPa. The analysis resolution is about 0.5–1 km for WALES and 1–2 km for IASI. The latter is in agreement with results obtained by Rabier et al. (2002). In short, the vertical resolution of WALES is about twice as sharp as that of the advanced IR. Again, best conditions are assumed for IASI. In practice, only a few hundred IASI channels will be used in NWP, not the full set. Also, some level of interchannel error correlation will exist, thereby reducing the information content. Some spikes are noted in WALES analysis vertical resolution, such as for the *U.S. Standard Atmosphere, 1976* near 650 hPa. These are correlated with the higher analysis error in Fig. 3. Such spikes occasionally occur at the transition height between two differing pairs of lidar wavelengths (see ESA 2001).

**Table 3. Mean WALES and IASI relative errors below 250 hPa based on Fig. 3.**

| Selected atmospheres | WALES | IASI |
|---|---|---|
| Subarctic winter | 7.30 | 15.93 |
| Subarctic summer | 6.54 | 10.51 |
| Midlatitude winter | 6.80 | 13.95 |
| Midlatitude summer | 7.43 | 9.03 |
| *U.S. Standard, 1976* | 8.02 | 10.50 |
| Tropics | 7.04 | 8.55 |
| Average | 7.19 | 11.41 |

*Alternative comparison.* The vertical extent of WALES, advanced infrared, and radiosondes were studied by an alternative method from a vertical cross section. The advanced infrared sounder used in this study is AIRS, which belongs to the same family as IASI. The cross section extending from 90°S to 90°N was extracted from a 6-h forecast valid 24 May 2001 at 0600 UTC at 1° × 1° resolution. From these data, WALES backscatter profiles were simulated, and the analytical model was applied to derive error profiles including the effects of clouds.

As seen in the IASI study, the error starts to increase rapidly in the tropopause region. The vertical extent was defined as the height where, starting from the top, the errors drop below 30%. Insisting on 20% would lower that height by about 0.5 km. In comparison, the vertical extent associated with radiosondes can be inferred taking as a limit the air temperature greater than 233 K [assuming that no reliable measurement is possible at colder temperatures; see Schmidlin and Ivanov (1998)]. One of the highest and strongest response functions associated with AIRS was selected from the humidity Jacobian $J(q)$ (variation of brightness temperature with $q$), which was computed for the cross section. The channel is number 1738 at 6.61 $\mu$m, a dominant water vapor absorption band. Starting from the top of the atmosphere, the level where $J(q)$ becomes significant (i.e., > 0.05 K change in brightness temperature per 10% change in $q$) identifies the maximum height where AIRS provides humidity information. Figure 5 compares the clear-sky vertical extent for the three data sources. The advantage of WALES is obvious and very significant, notably in high-latitude regions. The results are in line with the

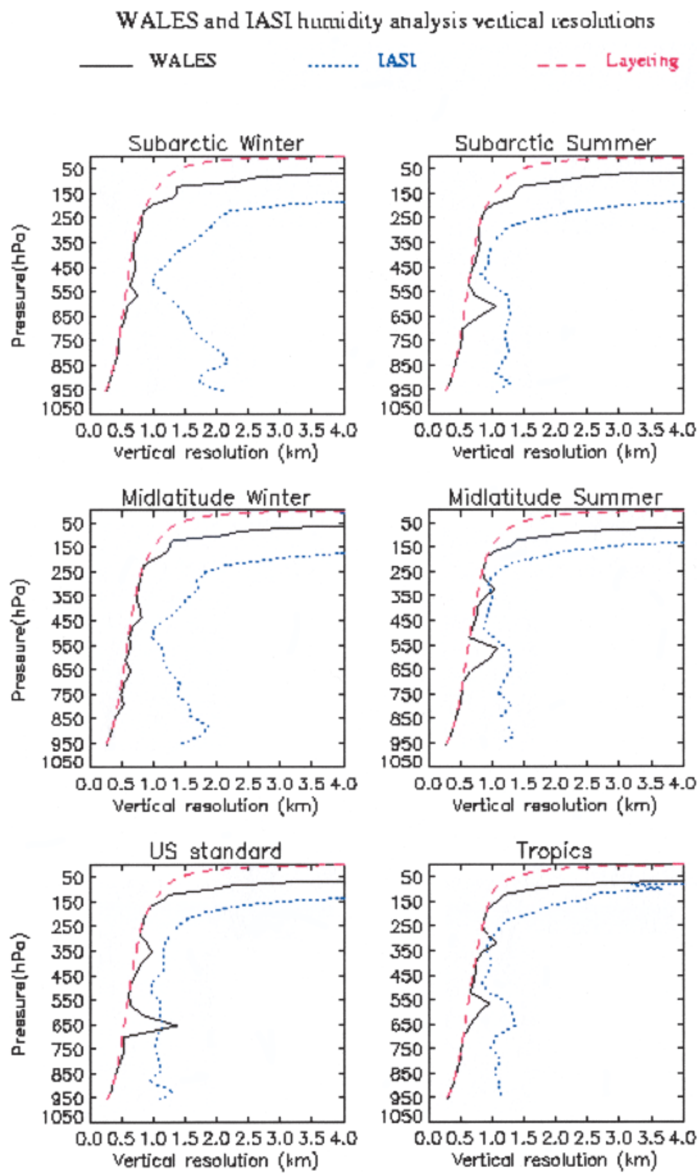


**Fig. 4. WALES (solid black lines) and IASI (dotted blue lines) specific humidity analysis vertical resolutions for the selected atmospheres. The resolution of the layering is also indicated in dashed red lines on each panel.**

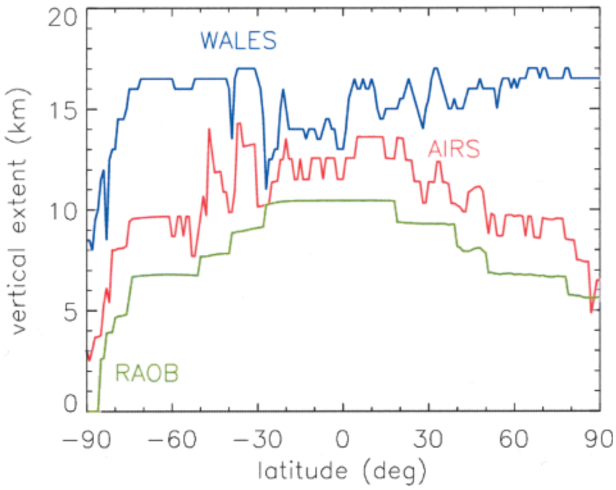


**FIG. 5. Comparison of the vertical extent of WALES (top blue curve), AIRS (middle red curve), and radiosonde observations (RAOB; bottom green curve) based on simulations from a 90°S–90°N cross section valid 24 May 2001 at 0600 UTC.**

IASI study, although the overall WALES advantage is more marked, especially in cold latitudes. The unique humidity information provided by WALES in the lower stratosphere between 100 and 250 hPa is one of the key advantages of the mission. The mean vertical extent for the cross section is 15.4 km (114 hPa) for WALES, 10.3 km (252 hPa) for AIRS, and 7.9 km (363 hPa) for radiosondes.

Comparisons of the loss of data volume due to clouds can also be made. This involves simulations of the impact of clouds on WALES errors and equally complex simulations of the use of IR channels above clouds. Such work is beyond the scope of this paper. Clearly however, the loss of volume due to clouds is much larger for IR soundings than for WALES. Indeed, WALES can provide profiles above cloud tops with low loss of quality. From IR sounding, however, the cloud-height determination is uncertain, and a margin of security dictates to use only channels sensitive up to about 1 km or more above the inferred cloud top. More importantly, IR radiances are very sensitive to cloud. Therefore strict quality control rules are used, resulting in substantial rejected data. In contrast, thin clouds have low impact on WALES retrievals. Finally, the very small field of view of WALES's individual pulses (about 40 m) allows soundings to be obtained through the gaps in broken cloud fields, provided the number of returned pulses remains sufficient to keep a desired accuracy. It is also possible to detect if, within the integration length, there are large variations of humidity, in which case the error is larger.

**SPECIFIC IMPACTS.** *Determination of the NWP background covariance matrix.* NWP forecasts start from an initial state of the atmosphere called analysis, and analyses are typically made every 6 h. Each analysis represents a blend of the information coming from the observations and that provided by a background estimate. The latter is typically a 6-h forecast. To get an optimal analysis, an essential piece of statistical information is the error associated with both observations and background (see appendixes A and B). The background covariance matrix **B** is typically defined by month and latitude for the diagonal elements (errors by level). However, the off-diagonal elements are defined assuming a global error correlation matrix between vertical levels. For the humidity variable, no correlation is assumed with other variables such as temperature and wind, although some correlations between humidity and temperature are believed to exist, especially at fine scales (Berre 2000). Because of the difficulty of inferring the **B** matrix from real observations over data-sparse regions, extensive use is made of the so-called "NMC (National Meteorological Center) method" (Parrish and Derber 1992), which is based on the difference between different length forecasts valid at the same time. Some scaling is usually done to better fit the magnitude of errors obtained from collocations of 6-h forecasts with radiosondes.

At the Meteorological Service of Canada (MSC) and the Met Office, the humidity variable is ln($q$), where $q$ is specific humidity. Errors are then defined by the relative quantity $dq/q$. This relative error typically increases with height from 20% at the surface to about 100% at the tropopause, according to MSC (Garand 2000), while at the Met Office, the error is topped at 46% above 300 hPa (English 1999). This is an indication that our knowledge on background humidity errors is poor. For the assimilation of 6.7-$\mu$m radiances (available from most meteorological satellites) sensitive to both temperature and humidity, a poor estimate of background humidity errors impacts negatively on the analysis of both variables. Garand (2000) has shown that a 20% change in the ln($q$) error standard deviation may lead to differences in temperature as large as 0.2 K. It was also shown that improving humidity error estimates is a much more pressing issue than improving temperature error estimates.

WALES will allow a vastly improved determination of the **B** matrix (variance and vertical correlation) for the humidity variable from the global and continuous ensemble of profiles it will provide. In that sense, even if WALES data are not assimilated, they will have a positive impact on NWP. WALES will in fact represent a unique source to get **B** matrix estimates at levels above 300 hPa or where the atmospheric temperature is below the limit for radiosonde humidity measurement, that is, 233 K (Elliott and Gaffen 1991).

*Applications in climate research and atmospheric modeling.* In considering the benefits of the WALES mission for climate research and atmospheric modeling, it is useful to address two distinct but related aspects. The first aspect concerns the contribution of WALES as a unique research mission providing a global humidity dataset in the 2008–12 time frame. The second aspect concerns the dual role of WALES as a mission to demonstrate the utility of a new spaceborne humidity observing technique and the wider implications this has for future humidity observation strategies.

RESEARCH APPLICATIONS OF THE WALES DATASET. In the context of a unique research mission providing a global humidity dataset with high vertical resolution and low bias, one of the major benefits of WALES lies in its relation to the other significant humidity datasets anticipated around 2010. These other datasets are primarily those derived from radiance observations made by the passive MW and IR systems employed for operational weather prediction. Because of its low bias, the WALES humidity dataset will be valuable as an absolute standard for improving and calibrating the retrieval algorithms of the passive systems. With such improvements, humidity datasets derived from passive systems will be more suitable for quantitative studies of climate variability and atmospheric processes, especially in the upper troposphere and lowermost stratosphere.

To be sure, further research is required to optimize application of WALES data for validating and calibrating passive systems. Relative to the passive systems, the WALES measurement volume has higher vertical resolution and higher cross-track horizontal resolution, but lower cross-track sampling. Consequently, we place a high priority on establishing the best ways to account for the different spatial characteristics of the respective systems.

In a similar vein, we see great scope for blending WALES data with complementary water vapor observations. It is easy to envisage many climate applications of successors to the National Aeronautics and Space Administration (NASA) Water Vapor Project (NVaP) dataset (Randel et al. 1996), in which the low bias and the good vertical resolution of WALES profiles are combined with the horizontal coverage provided by passive sounders and in situ measurements provided by radiosondes.

The applications mentioned so far in this section concern the impact of WALES on the provision of humidity datasets and by implication the indirect impact on the climate research and atmospheric modeling communities. However, WALES data will also be of direct use to these communities, notably to atmospheric model validation through diagnostic studies of water vapor processes. One of the major issues for climate modeling and understanding is to develop parameterizations that accurately account for unresolved water vapor processes, down to the scales relevant to individual convective events, condensation, precipitation, and cloud microphysics. A similar issue arises for numerical weather prediction since neither climate models nor NWP models will resolve all of these scales in the near future. The good vertical resolution and along-track sampling of WALES data will provide new information to complement other humidity data used for model validation. In this application, our priority would be to obtain insight into the interplay between convection and dynamics in determining humidity profiles on the vertical and horizontal scales characteristic of global weather and climate models. These insights will in turn contribute to the identification of systematic errors in models and improved parameterizations. It is worth restating that the quality of radiosondes does not allow identification of systematic humidity biases above 500 hPa (Ross and Elliott 1996). In contrast WALES will provide high quality data up to 100 hPa (Fig. 5). Such low-bias data are suitable as constraints in the "model to satellite" approach to model validation; a preliminary example is given in appendix C.

IMPLICATIONS FOR THE FUTURE. We now address the role of WALES as a mission to demonstrate the utility of active profiling of humidity from space, and the wider implications this has for future humidity observing. Experience with ground-based and airborne water vapor DIAL systems and ongoing scientific and technical studies indicate that the observation requirements specified for the WALES mission are ambitious but can be met in the 2010 time frame. We see several important areas for further development and exploitation that would follow a successful demonstration by WALES of the spaceborne water vapor DIAL technique.

First, long-term global monitoring of water vapor and climate change would be enhanced substantially by a series of spaceborne water vapor DIAL systems, exploiting their low bias and the self-calibrating property of the measurement technique (Ismail and Browell 1989; Bösenberg 1998). Assuming that WALES-type observations become a regular component of the Global Observing System, climatic trends in humidity will be inferred with far less ambiguity. This is not to suggest that WALES instruments would make other humidity observing techniques obsolete. We have already argued that spaceborne water vapor DIALs would facilitate validation and improved calibration of other humidity sensors. The issue for the future would therefore be to determine the best long-term combination of observing systems. One scenario would be to schedule spaceborne DIAL missions to coincide with the overlap period between different passive satellite systems, in order to improve the long-term consistency of such datasets. Other important areas for development would be performance improvements to permit an increase in vertical resolution to say 0.5 km throughout the entire troposphere, together with reductions in the horizontal integration distance to match inevitable improvements in atmospheric model resolution. Development of scanning DIAL capabilities would also help to reconcile the different spatial characteristics of the different humidity observing systems.

**DISCUSSION.** Adequate qualitative, let alone quantitative, global description of water vapor is still lacking, for a number of reasons. These include the large dynamic range of specific humidity and its high temporal and spatial variability. The radiosonde archive, the longest available data source, suffers from the uneven quality of the observations in addition to intrinsic limitations of the sensors. Satellite observations by passive remote sensing techniques provide better global coverage but lack the vertical resolution and low, well-characterized, time-independent bias required for an absolute standard.

By employing an active remote sensing technique that provides good vertical resolution and high data quality, the Earth Explorer WALES mission is expected to answer a long-standing need for humidity observations in climate and NWP applications. A successful WALES mission will demonstrate the impact of a spaceborne DIAL system in improving the understanding, modeling, and validation of the water and energy cycle, radiative transfer, physical processes, aerosol, clouds, and atmospheric chemistry.

WALES will be particularly powerful for the calibration of passive remote sensing techniques. The DIAL system will provide a stable absolute reference to calibrate water vapor–sensitive infrared and microwave channels. This improvement will provide a better spectroscopic calculation to remove water vapor signal from infrared and microwave channels, in turn improving the retrieval of trace gases, temperature, and cloud properties such as emissivity, cloud-top temperature, etc.

This study shows that a spaceborne DIAL system can potentially greatly increase the amount of humidity information along the vertical that may be assimilated into NWP models, in a more striking way than IASI. This result is confirmed by the different concepts examined in this study, in terms of number of degrees of freedom for signal, humidity analysis error standard deviation, as well as humidity analysis vertical resolution. This study shows a larger vertical extent of the WALES retrievals and higher quality data when compared to advanced infrared sensors. However, the potential benefit of WALES in the analysis does not imply necessarily a forecast improvement. The potential impact of WALES on forecast improvement should be proven in a three- or four-dimensional context with real profiles and background error covariance matrices that can vary with space and time.

The feasibility of the required type of observations has been proven recently by ground-based and airborne DIAL systems. The technical challenge of translating this experience into a spaceborne DIAL is currently under investigation within phase A studies and will lead to a final configuration that will satisfy the technical and scientific requirements of the mission. In view of this and the considerable scientific benefits expected for climate and NWP, it is very timely to implement the WALES mission.

Finally, it is worth mentioning that a successful performance of the WALES mission will provide the foundation for a new generation of active water vapor remote sensing systems. WALES is based on a scalable transmitter and receiver. Therefore, the resolution of future systems can be significantly increased further by application of the next generation of laser transmitters and receivers with higher power and aperture, respectively. Additionally, once the idea behind WALES has been successfully demonstrated, the coverage of future systems can be improved by implementing a scanning capability to allow for cross-track measurements and by simultaneous operation of DIAL systems on different satellites.

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## APPENDIX A: INFORMATION CONTENT CONCEPT.

The general framework of this study is linear optimal estimation theory in the context of NWP (Rodgers 2000). NWP analyses typically combine information from a first guess with observations. A statistically optimum analysis requires good statistical knowledge of errors associated with both components. Several measures of information content can be derived based on the expected reduction of the analysis error obtained from observations. In this exercise the observations have to be linked to the model state variables $X$. This link is performed via the observation operator $\mathrm{H}(X)$ that projects the model control variables onto the observation space. This operator is the identity operator when measurements are directly comparable to model variables: it is the case for absolute humidity profiles provided by the WALES mission on the condition that the observed profile levels are the same as the model levels (otherwise H must include an interpolation calculation). However, when a remote measurement is made, the measured quantity is often a more or less complicated function of the parameter that is actually required. The typical atmospheric example is electromagnetic radiation emerging from the atmosphere, such as IASI radiances. In this case the observation operator $\mathrm{H}(X)$ is a radiative transfer model whose inputs are temperature and humidity profiles (plus trace gases here assumed known). The output is a radiance or brightness temperature. If the atmospheric model is characterized by a background error covariance matrix $\mathbf{B}$($N \times N$ variables, including temperature and humidity profiles, plus surface pressure) and the observation by an observation error covariance matrix $\mathbf{O}$($M \times M$ types), it can be shown that, if $\mathbf{H}$ can be considered linear, the analysis error $\mathbf{A}$ is linked to $\mathbf{B}$ and $\mathbf{O}$ by

$$\mathbf{A}^{-1} = \mathbf{B}^{-1} + \mathbf{H'}^{\mathrm{T}}(X)\ \mathbf{O}^{-1}\ \mathbf{H'}(X), \qquad \text{(A1)}$$

where superscripts –1 and $T$ denote matrix inverse and transpose, respectively; $\mathbf{H'}$ is called "Jacobian matrix" ($M \times N$), in which each element is the partial derivative of the forward model output $\mathrm{H}(X)$ with respect to a state vector element. As indicated above, $\mathbf{H}$ and $\mathbf{H'}$ are the identity matrix for WALES. For IASI data, $\mathbf{H'}$ is the Jacobian matrix representing the partial derivatives of brightness temperatures with respect to the $N$ control variables. Strictly speaking, WALES retrievals are also based on an operator transforming raw backscatter measurements into humidity profiles [based on Eq. (1)]. However, for this study, we assume that humidity profiles are available from WALES along with a local estimate of the error profile.

Observation, background, and analysis variances are given by the diagonal elements of $\mathbf{O}$, $\mathbf{B}$, and $\mathbf{A}$, respectively. It is worth noting that for each variable the analysis error is necessarily smaller than both the observation and background errors. One of the simple measures of performance is the "degrees of freedom for signal" defined as

$$\mathrm{DFS} = \mathrm{Tr} - (\mathbf{I} - \mathbf{A}\ \mathbf{B}^{-1}), \qquad \text{(A2)}$$

where Tr denotes matrix trace, and $\mathbf{I}$ the identity matrix. This quantity gives a global measure of the reduction of uncertainty or gain in information brought by the data (Rodgers 2000). If the DFS pertaining to humidity on $L$ levels is calculated, then clearly the maximum value of DFS is $L$. This means that $L$ independent pieces of information are obtained. Conversely, DFS will tend to zero if the analysis provides little improvement over the background. For a more detailed diagnostic of the quality of the analysis, one can use an estimate of the vertical resolution associated with the resulting profiles. The vertical resolution at each level $i$ in the vertical, following Purser and Huang (1993), is given by the ratio of the layer thickness ($dz$) chosen for the analysis of the variable and the corresponding diagonal element of the model resolution matrix (MRM):

$$\mathrm{VR}_i = dz_i / \mathrm{MRM}_{ii}, \qquad \text{(A3)}$$

where $\mathrm{MRM} = \mathbf{KH'}$; $\mathbf{K} = \mathbf{AH'}^{\mathrm{T}}\ \mathbf{O}^{-1}$ is called the Kalman gain matrix; and $\mathbf{K}$ can be interpreted as the generalized inverse of $\mathbf{H'}$, allowing us to reconstruct the atmospheric profile from the data. MRM (with diagonal elements $\leq 1$) indicates to what extent the analysis represents reality. In the ideal case where the analysis is equal to the true atmospheric state, MRM is equal to the identity matrix, and the vertical resolution of the analysis is given by the resolution of the model layering.

For comparing WALES to IASI performances it was necessary to interpolate the atmospheric profiles onto the 43 fixed pressure levels as required in the radiative transfer model for IASI (RTIASI; Matricardi and Saunders 1999). These levels range from 0.1 hPa (about 65 km) to 1013.25 hPa, characterized by a thin layering in the lower troposphere and a broader layering in the stratosphere and lower mesosphere. RTIASI not only computes brightness temperatures (BT) [forward model H($X$)], but also the Jacobian matrix $\mathbf{H'}(X) = d\mathrm{BT}/dX$. Details on the estimation of the **O** and **B** matrices can be found in appendix B.

**APPENDIX B: ESTIMATION OF THE O AND B MATRICES.** Details on how WALES observations and retrieval errors are simulated are beyond the scope of this paper and will be the object of a future specific publication. WALES errors used in this study are very similar to those presented in the WALES Report for Assessment (ESA 2001). Three independent research teams, those of DLR, Hohenheim University, and Basilicata University, led to very similar error profiles. WALES errors are computed assuming an integration length of 100 km. The simplicity of the radiative transfer equation for the WALES signals allows us to calculate directly the error propagation of noise. Three different noise sources have been considered: noise due to Poisson statistics in the backscatter signals, noise due to the daylight background signal, and noise due to amplifier and detector noise currents. It is assumed that these are the most important error sources and that these various errors are statistically independent.

The error analysis showed that the noise contribution resulting from solar background radiation is the most limiting factor with reference to data quality for all investigated climates. However, we found that this unwanted background radiation could be significantly reduced by selection of a sun synchronous dawn/dusk orbit and operating the WALES instrument in the vicinity of strong water vapor absorption lines. In this case, the atmosphere itself acts as an optical filter by strongly absorbing the background radiation at solar zenith angles greater than 60°. Ehret et al. (2002) and Bauer et al. (2002) showed that even the increase of the background signal due to the cloud albedo has a rather low influence on the error profile. Therefore profiles above cloud are hardly affected. However, WALES can even perform measurements below clouds if the optical thickness of clouds is low enough (approximately less than 0.3). Here, we restrict our evaluation to the clear case because the evaluation of IASI under partly cloudy conditions is quite involved. Further details of the error analysis can be found in Wulfmeyer and Walther (2000a,b). Their analytical model can also be applied for performance analyses of spaceborne DIAL systems. Additional systematic errors are likely smaller than 5% and have been neglected in this comparison.

Even though correlations between adjacent channels are ignored in the IASI observation error covariance matrix, an observation error covariance matrix with nonzero elements off the diagonal of **O** has been used for WALES. For IASI computations the scene is assumed to be cloud-free, and a constant error of 0.2 K coming from the radiative transfer model noise is added to the measurement error. Values of observation noise range from 0.1 to 0.22 K at wavenumbers 645 to 2250 cm$^{-1}$ and increase up to 1.9 K at 2760 cm$^{-1}$. These values are valid at a temperature of 280 K, and are converted at the appropriate scene temperature for each wave number and each profile.

The background error covariance matrix is typical of a state-of-the-art NWP model as in previous studies (Prunet et al. 1998; Collard 2000; Rabier et al. 2002). The **B** matrix used in this study is the same as in Rabier et al. (2002); it is built from the 60-level European Centre for Medium-Range Weather Forecasts (ECMWF) covariance matrix representing short-range forecast errors. This matrix contains specific humidity error variances and covariances. As a consequence these values do not depend on the atmosphere. At the Met Office and the MSC, the error covariances are expressed in terms of relative errors $dq/q$, allowing the error profile to be weighted by the specific humidity profile itself. In our approach, based on this interesting feature, the relative error standard deviation $dq/q$ is kept constant at each level, linearly increasing from 20% at 1013.25 up to 90% at 0.1 hPa, and the error correlation matrix is the one extracted from the 60-level ECMWF covariance matrix as defined in 2002. For direct comparison between WALES and IASI data at comparable horizontal scales, the IASI brightness temperature errors have been reduced by a factor of 8½, as they were provided with a 12-km horizontal resolution with a distance between each pixel of 50 km.

**APPENDIX C: WALES DATA AS A RADIATIVE CONSTRAINT.** The "model to satellite" approach to model validation, in which satellite-observed radiances are compared with model-simulated radiances (Morcrette 1991; Roca et al. 1997; Chevallier et al. 2001; Ringer et al. 2002, manuscript submitted to *Quart. J. Roy. Meteor. Soc.*), will benefit from low-bias WALES profiles. A major uncertainty in the approach concerns the scope of compensating errors in the calculation of model-simulated radiances, as could arise from inaccurate radiative transfer scheme and systematic errors in modeled water vapor fields. Thus, WALES data will have an important role to play in constraining uncertainties associated with the radiative effects of water vapor. Such constraints will also be useful for better understanding of the earth's radiation budget and, as previously mentioned, for the calibration and validation of passive remote sensing instruments.

To illustrate the quantitative constraints provided by low-bias water vapor profiles, we have used the Edwards–Slingo (1996) radiation scheme to compute outgoing longwave radiation (OLR) for a number of atmospheric conditions. The results are shown in Fig. A1. The conditions in the control computation have the *U.S. Standard Atmosphere, 1976* water vapor profile and a typical present-day $CO_2$ mass mixing ratio (524.1 ppmv), resulting in 293.4 W $m^{-2}$ OLR (Control diamond in Fig. C1). Corresponding computations of OLR using water vapor profiles from WALES simulations were found to be dominated by the simulated biases rather than the simulated random errors and are shown as the vertical bars in Fig. A1. As expected, a 5% dry bias increases OLR (to 294.3 W $m^{-2}$) while a 5% moist bias decreases OLR (to 292.7 W $m^{-2}$). Thus, water vapor profiles with biases limited to 5% constrain the percentage change in OLR to around 0.4%. By contrast, other work calculates that a 20% uncertainty in cloud optical depth and liquid water content gives rise to 5 W $m^{-2}$ uncertainty in OLR (Miller and Stephens 2001). Analogous OLR computations have been performed with double the amount of $CO_2$ and are also shown in Fig. A1. Again, limiting the uncertainty in the water vapor profile is important for estimating OLR accurately. The constraints provided by accurate water vapor profiles considered here are most relevant to validating radiative transfer in atmospheric models and to minimizing systematic errors in climate change simulations. It is likely that even greater accuracy in water vapor observations would be required for detecting and attributing climate change. A natural extension of this work would be to examine the potential of WALES for constraining spectrally resolved radiation.

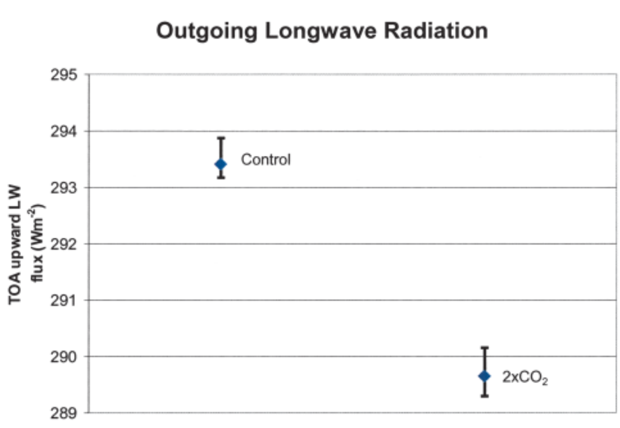


**FIG. A1: OLR at top of atmosphere. The error bars show the constraints imposed by WALES data with moist and dry biases (5%). Ten noisy profiles have been averaged in each case and are virtually indistinguishable from simulations with the same biases and no noise.**

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